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Strengthen | Expand | Grow

Metrology driven manufacturing – From NIF to lithography optics

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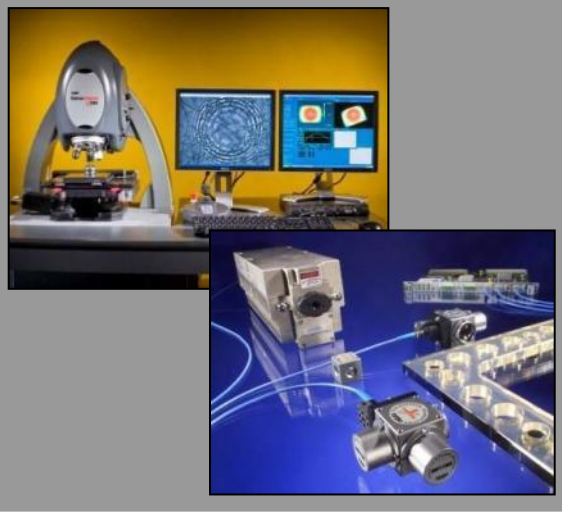
Acknowledgements:
- **DOE & LLNS esp. Chris Stolz and Joe Menapace**
- **Advanced Ligo**
- **EUV Customers**

Outline

- Introduction
- National Ignition Facility
- Advanced Ligo
- Extreme UV Lithography optics
- Conclusions

One Company – Two Operational Divisions

METROLOGY SOLUTIONS



Leading metrology systems for critical process control and advanced research

- Industrial/Precision Machining
- Optics/Photonics
- Semiconductor
- Data Storage
- Energy
- Academia/Research

- 3D Optical Profilers
  - Surface Roughness
  - Materials/Films Characterization
  - Critical Dimensions
- Laser Fizeau Interferometers
  - Surface Shape/Form
- Distance Measuring Interferometers
  - Lithography Stage Control
- OEM/Integrated Metrology
  - Semiconductor
  - Displays

OPTICAL SYSTEMS

OEM supplier of high precision integrated optical systems and components

- Defense & Aerospace
- Industrial
- Life Sciences / Medical
- Semiconductor

- Optical components
  - Lenses, Mirrors, windows…
  - Flats, spheres, aspheres, free-form…
  - Glass, ceramics, metals…
- Electro-Optical systems
  - Design & analysis
  - Prototypes and production
  - Lens assemblies, sources, sensors…

Optical Systems Division

Extreme Precision Optics

200+ highly skilled resources focused on high precision OEM optical systems design, development, and volume manufacturing.

Richmond, CA

Middlefield, CT

Costa Mesa, CA

Tucson, AZ

Precision Optics
Laser Fusion Optics

Electro-Optics Group
Costa Mesa – R&D
Tucson – Manufacturing

ZYGO Optical Systems Division also leverages from the additional 300+ resources and technology of the Metrology Solutions Division.

National Ignition Facility (NIF)

NIF building:

- **Located at Lawrence Livermore National Laboratory (LLNL)**
- **Size of about 3 football fields**
- **Requiring thousands of meter class size optics**

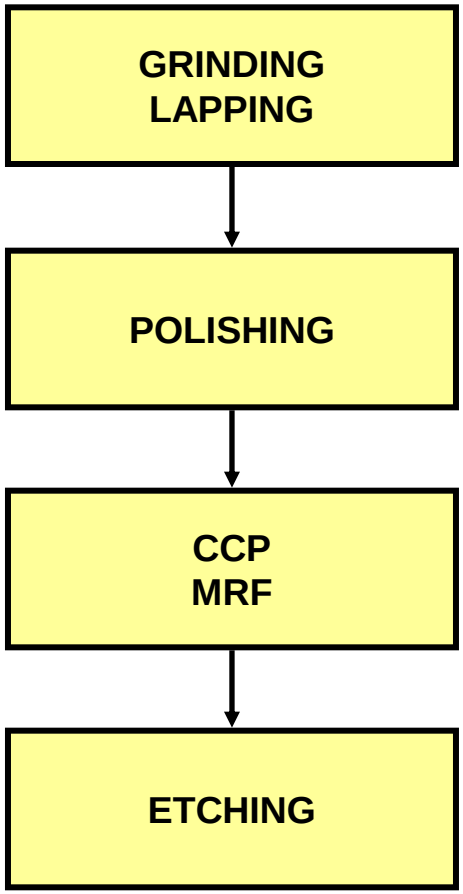
Credit: Lawrence Livermore National Laboratory

Laser Fusion Optic
Products and requirements

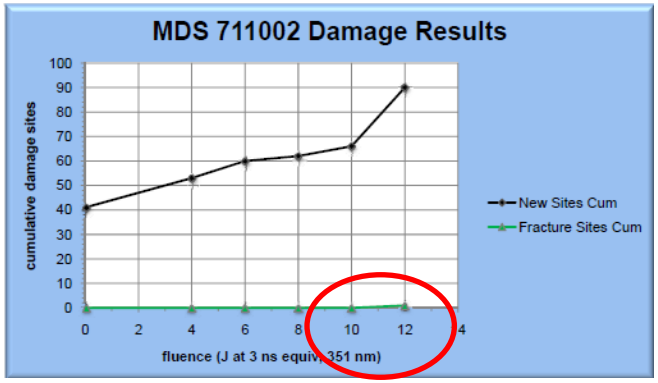
- 1,000's of optics:
  - Phosphate laser amplifiers of different configurations
  - Continuous Phase Plates (CPP)
  - Polarizers, mirrors, windows…
  - Substrates (thin plates, gratings…)
  - High-laser damage tolerant UV optics

- Requirements:
  - Optical Material Quality
    - High homogeneity
    - No bubbles / inclusions
  - Optical Performance
    - Global wavefront performance
    - Minimal slope gradients
    - Micro-roughness
  - Surface and Optic Quality
    - 30/10 or less scratch/dig & max scratch lengths
    - No sub-surface damage
  - Low breakage and damage occurrences
    - Optic material costs exceed finishing costs

UV Laser Damage Resistant Optics 3w Process Flow



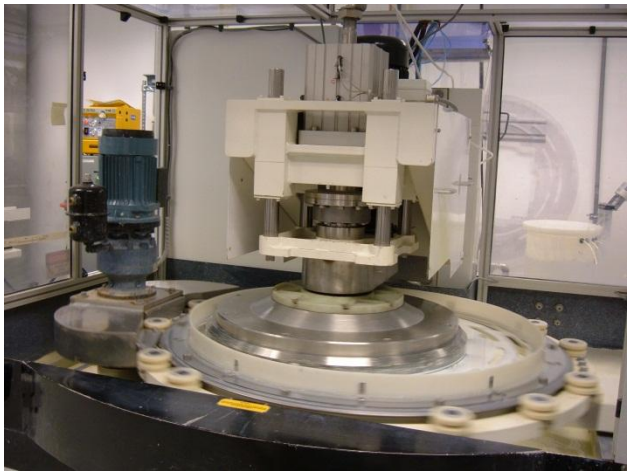
- Grinding / Lapping:
  - Initial shaping
  - Controlled Sub-surface Damage (SSD)
- Polishing:
  - Controlled SSD removal
  - Initial wavefront control
  - Manage surface defects
- CCP/MRF:
  - Manage Surface defects to final spec
  - Wavefront control to final spec
  - Laser Induced Damaged Threshold (LIDT) specification
- Etching

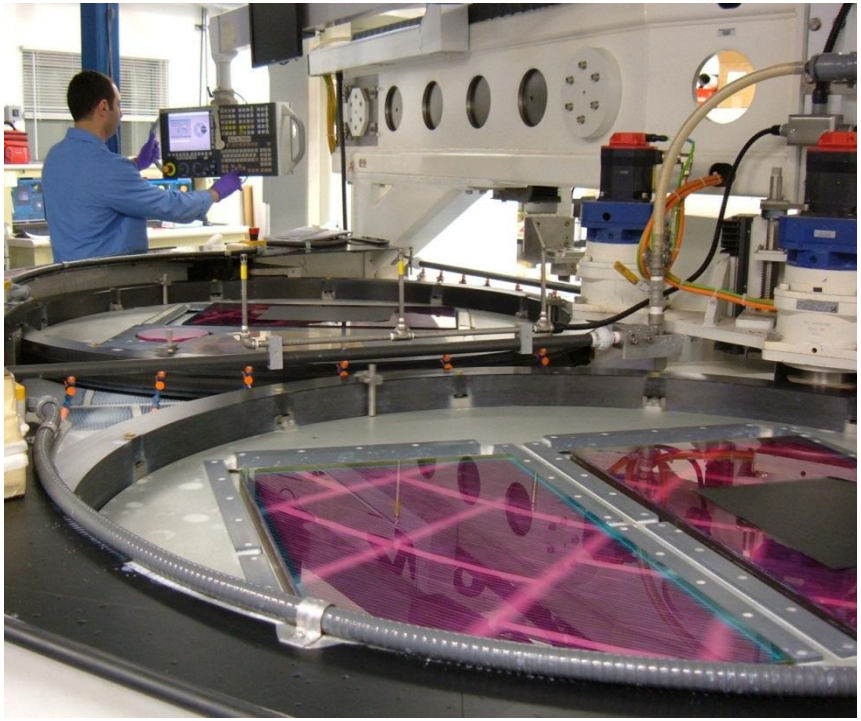


Credit: Lawrence Livermore National Laboratory – Dr. Joe Menapace

Polishing Process (Full Aperture)

- Large size pitch and high-speed synthetic lap polishing machines:
  - Custom made
  - From 1.2 meter to 4.26 meter (14')
- Single side and double side processes

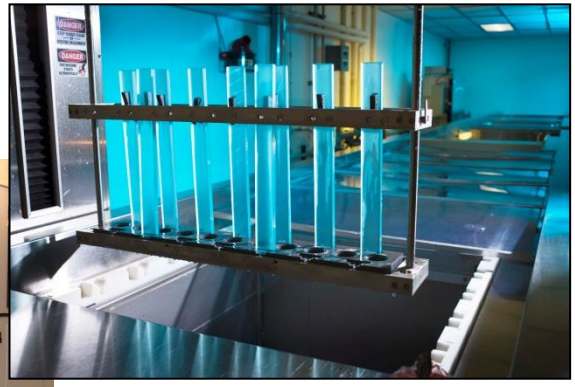


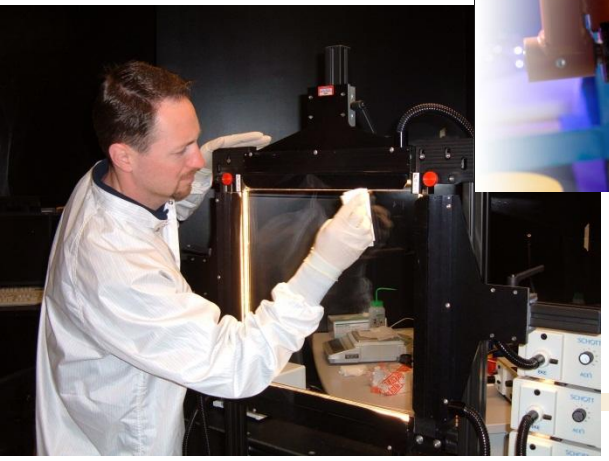


Polishing Process (Sub-aperture)

- Computer Controlled Polishing (CCP)
  - Custom made tools
- Magneto Rheological Finishing (MRF®)
  - Large installed based
  - Commercial tools:
    - Q22-Y
    - Q22-750P2
  - Custom made tools
  - Zygo early adopter of technology (> 10 years)

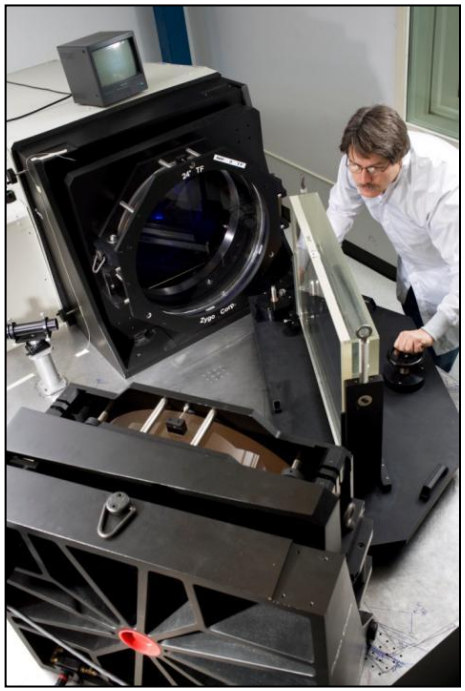
Etching, cleaning and inspection





- Final Cleaning & Inspection
  - Three clean rooms
  - Two automatic cleaning systems
  - Numerous inspection and material handling stations
- Packaging and Shipping

High Precision Metrology



In process and final metrology

- 24” and 32” interferometers enabling full aperture measurements
- NewView Microscopes
- Phase measuring interferometers
- Wavelength shifting interferometers

Dedicated environment

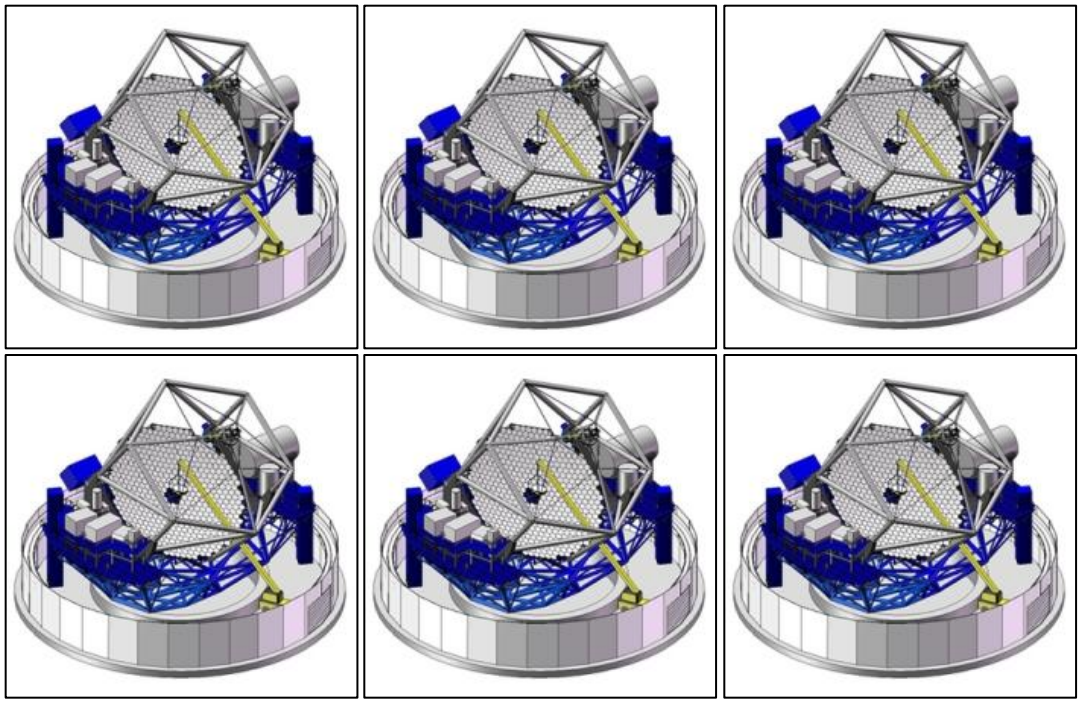
- **Temperature controlled**
- **Vibration controlled**
- **Remotely operated**

Extensive material handling equipment

- Ergonomic considerations
- Operators safety
- Optics safety

Largest producer of laser fusion optics in the world

- Over 6,900 Laser Fusion Optics produced to date (& counting…)
- Meter class optics

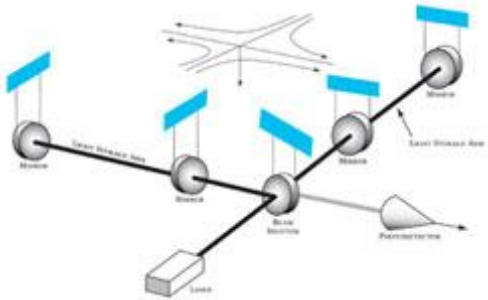


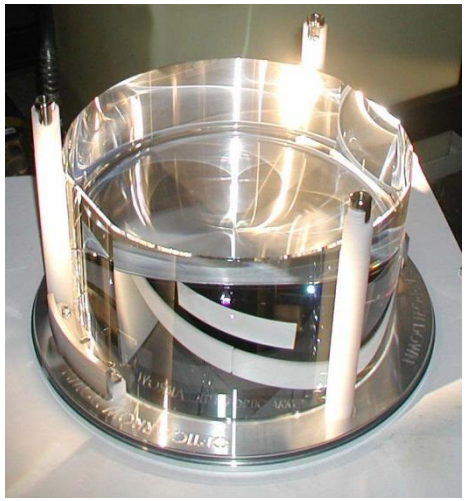
That is 4,200 m^2 polished or:

- ~0.6 Soccer Field
- ~1 American Football Field
- ~ 6 Thirty Meter Telescopes (TMT Primary Mirrors)
- ~10 Basketball courts
- ~ 125 James Webb Space Telescopes (JWST)

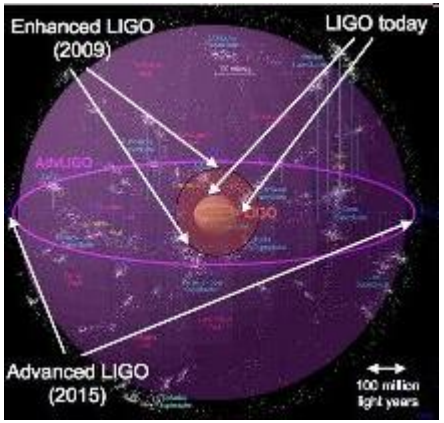
Advanced LIGO

- Laser Interferometric Gravitational-wave Observatories
  - Michelson interferometer with 4km arms
  - Detect gravitational waves created by cosmic events as predicted by Einstein's general relativity theory.
  - Located in Louisiana and Washington states
- Upgrade will provide 10x boost in sensitivity and 15x in detection distance
- Approx. Fifty ~340mm optics of 0.3nm rms quality





Advanced LIGO will have more than a factor of 10 greater sensitivity than initial LIGO. Since the volume of space that the instrument can see grows as the cube of the distance, this means that the event rates will be more than 1,000 times greater. Advanced LIGO will equal the 1-yr integrated observation time of initial LIGO in roughly 3 hours.



Credit: https://www.advancedligo.mit.edu/core.html

Advanced LIGO
Input and End Test Mass (ITM/ETM)

- Ø 340mm x 200mm thick
  - Weight ~40 kg / 88 lbs

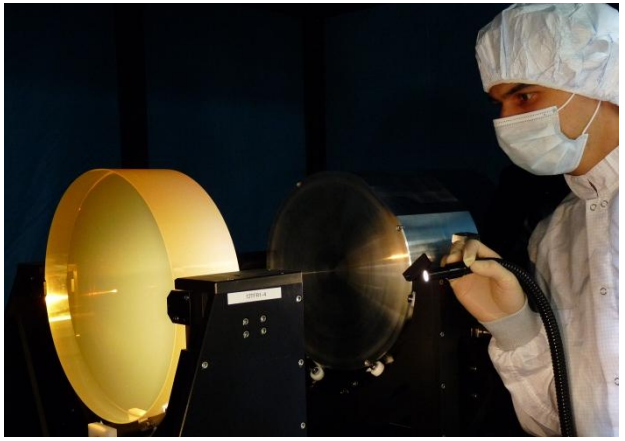
- Demanding polishing requirements
  - Very tight surface quality tolerance.
  - Concave Radius 2km
    - Corresponds to 5.6μm Sag over Ø300mm
  - Radius measurement uncertainty ±5m
    - Fabrication tolerance ±15m.
    - 5m radius error corresponds to 14nm Sag over Ø300mm
    - All 12 ITM/ETM parts matched to ±1m fabrication goal
  - Figure requirement < 0.3nm RMS

Advanced LIGO optics metrology

Measure figure and radius of parts with a 2km radius to the required precision

- **Using a custom 12-inch convex transmission sphere (TS)**

Zero-expansion ceramic glass transmission sphere for LIGO 2km radius parts



- **A TS with such a radius of curvature and this low level of uncertainty is a unique metrology solution because of the challenge in qualifying and fabricating it.**
  - **Radius uncertainty of ±2m**
    - **A qualified test plan and error budget allocation is used to manage the sources of error.**
    - **The radius of the TS is qualified against a flat, that has been calibrated by an absolute measurement method.**
  - **Radius stability of < 1m**
    - **Zero expansion ceramic glass qualified for internal homogeneity for very good transmission quality.**
  - **Support fabrication to <0.3nm RMS**
    - **The TS figure is calibrated to <0.15nm RMS by absolute, self-referencing methods.**

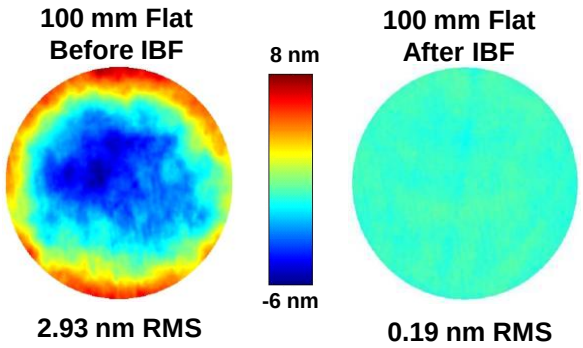
Advanced Technology for Asphere Fabrication

Computer Controlled Optical Surfacing (CCOS)

- Proprietary and export controlled technology developed internally
- Aspheres & precision sphere, flats, cylinders
- Configurable for glass, CaF_2, Zerodur, ULE, SiC, Si and other materials and wide range of part geometries
- Scalable beyond 1.5m
- Achievable specifications
  - 1nm rms Figure
  - 0.2nm rms Surface Roughness (glass)

Ion Beam Figuring (IBF)

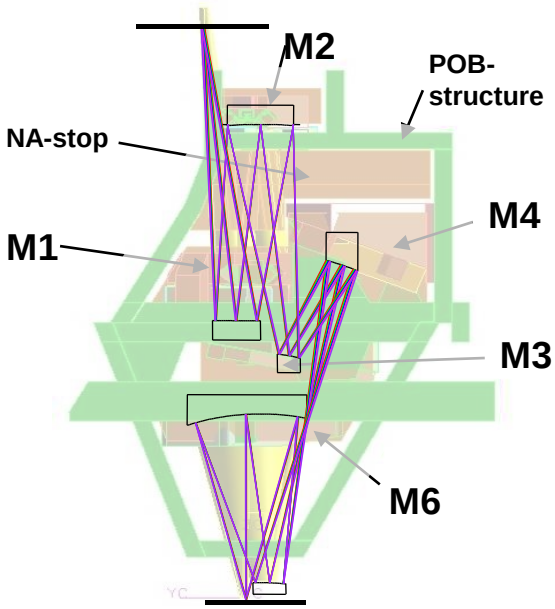
- Internally developed technology
- Utilizes an argon ion stream in vacuum to locally “polish” an optical surface
- Couples data from optical metrology with CCOS software to locally correct surface errors
- IBF offers significant advantages:
  - Flat, spheres, aspheres, free-form etc.
  - Surface figure < 0.25nm rms (λ/2500 @ 633nm)
  - No edge exclusion (unlike physical polishing methods)
  - Works on delicate and/or easily deformed surfaces, e.g. ultra-lightweight substrates (no print-through)
  - Can be applied to surface geometries that are not accessible to conventional polishing tools
  - No scratching
  - Zerodur, ULE, glass, ceramic, Si, CaF_2 etc…

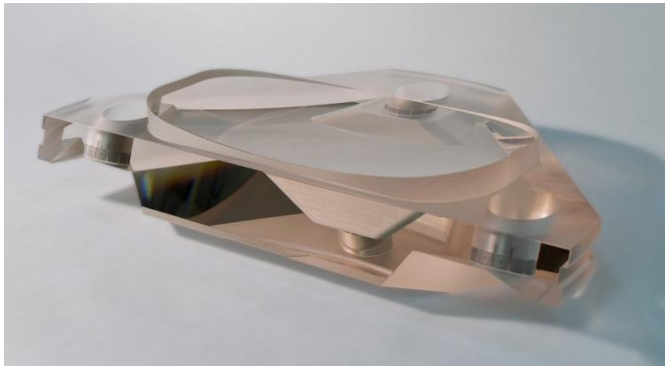


Surface error before and after one IBF iteration

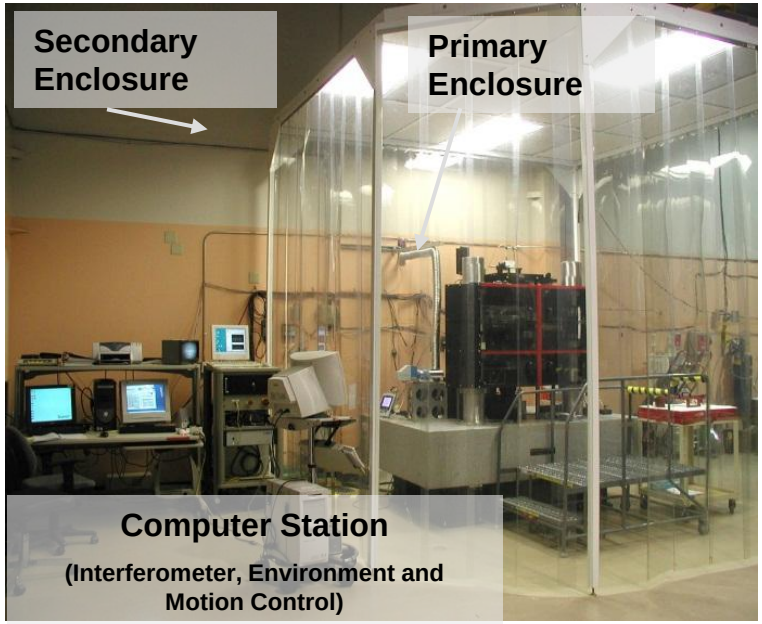
EUV Mirror

- Mirror for EUV lithographic projection system.
  - 13.5nm wavelength, 0.25NA, 4x reduction, less than 30nm printing resolution.
- Off-axis aspheric mirror
  - 500+ mm concave surface with a few um of aspheric departure
    - Kidney shape clear aperture
  - Off-axis: The optical axis is completely off the mirror substrate.
- Testing to support manufacture.
  - < 0.1nm RMS Figure requirement



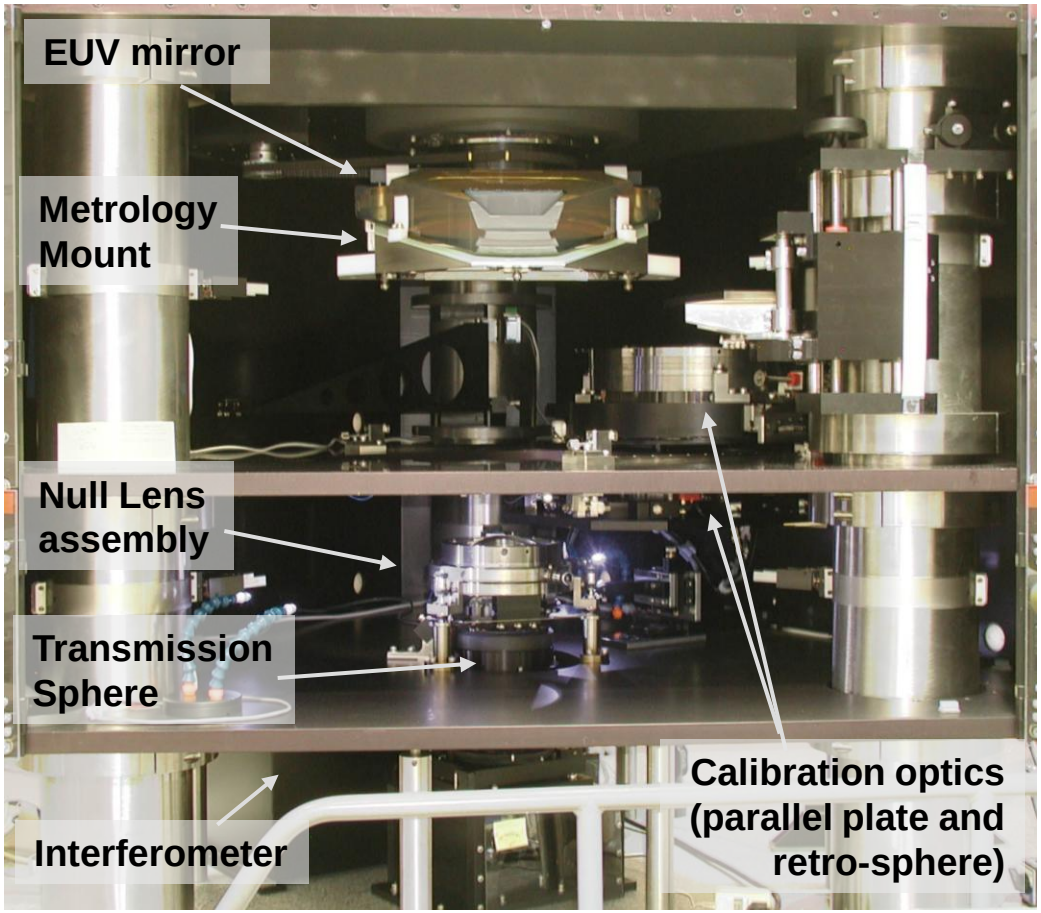


Mirror Figure Metrology



- Temperature controlled room
- Multiple enclosures

The Primary Enclosure contains all the critical optical components.



EUV Mirror Figure
Reproducibility

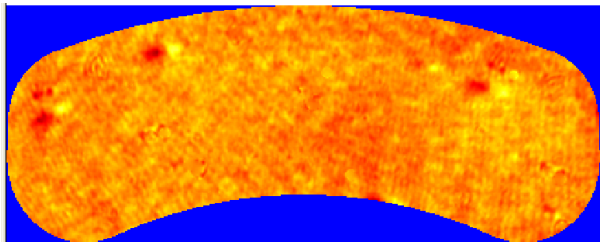
- A refractive null test was designed and built to test the EUV mirror:
  - Measure the asphere and perform calibration of the test optics
    - Support the <0.1nm RMS surface requirement
  - Vertical test cavity to meet mounting and gravity orientation requirement
  - Support optical axis location measurement

- The level of accuracy of the test is achieved by:
  - Identification and Control of all error sources through a rigorous error budgeting process.
  - Ultra-precise measurement process
  - Stability of the test
    - Thermal stability of the component and monitoring of the temperature drift.
    - Great mechanical stability and mount reproducibility

- Typical Figure measurement Reproducibility of the EUV figure test is about 50pm.

Example of test reproducibility:

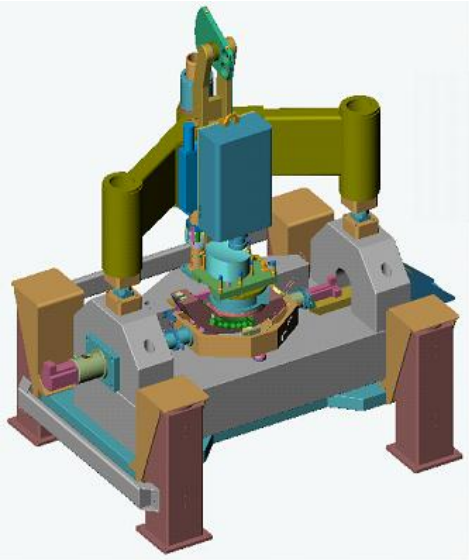
difference between an individual test and average of multiple tests

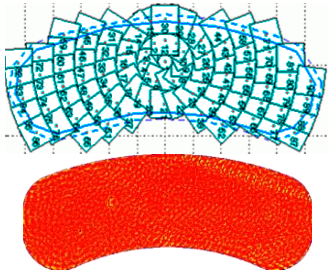


0.042nm RMS, 0.496nm P-V

SASHIMI and PSD

- Interferometer to measure high resolution, full aperture Mid-Spatial Frequency surface error by combining small aperture maps
  - Bridge the gap between figure interferometer and Phase-Measuring Microscope (PMM)
  - Provide full aperture data to support manufacturing processes.



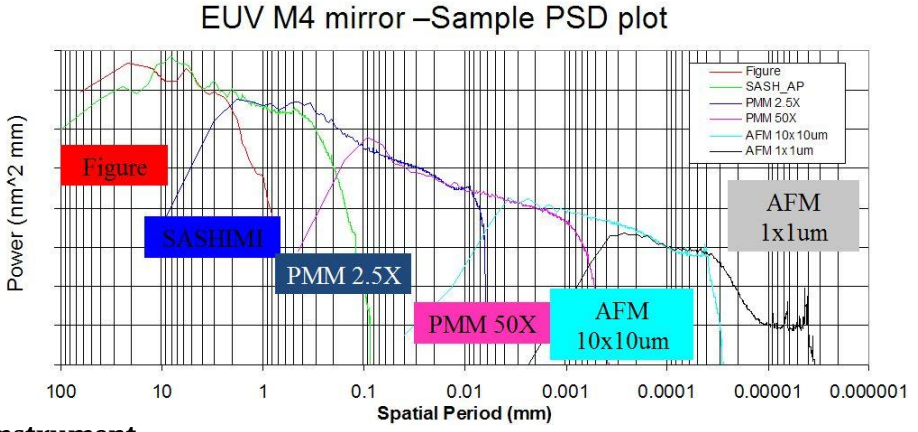


EUV M4 Mirror

SASHIMI Data [5-0.5mm]

RMS 0.10nm

- Full spectrum surface characterization constructed with multi-instrument PSD plot.
  - Each Instrument has a limit to its spatial resolution. A power spectral density (PSD) process is used to characterize each instrument's response.
- The Figure, SASHIMI, PMM and AFM PSD's are combined to create a composite with a much larger range than can be acquired by a single instrument.



SASHIMI: Sub-Aperture Surface Height Interferometric Measuring Instrument

Conclusions

- From making thousands of laser fusion optics…
- … to long RC spheres with tight requirements…
- …to probably some of the best optics ever made (EUV-L)…
- … a common theme:
- Metrology is key to success!

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